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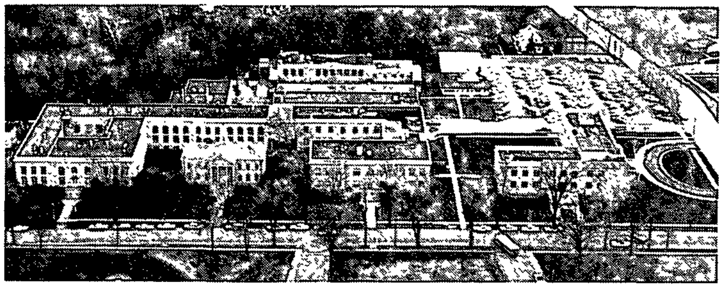

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# COMPRESSIVE STRENGTH RETENTION DURING FLUTING OF MEDIUM. PART 1. STRENGTH LOSSES IN FLUTING.

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# COMPRESSIVE STRENGTH RETENTION DURING FLUTING OF MEDIUM. PART 1: STRENGTH LOSSES IN FLUTING

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## ABSTRACT

This article is the first in a series devoted to factors that affect the compressive strength of medium. In this first article the retention of compressive strength during fluting is discussed. Our results indicate that the flat crush and edgewise compressive strength (ECT) potentials of corrugated board, which are dependent on the medium, are greatly reduced by the fluting process. This occurs because fluting causes large reductions in the edgewise compressive strength of the medium, under both hot and cold forming conditions. The reductions in strength are caused by the high bending and tension stresses induced in the medium during fluting. There are opportunities to improve box performance or save fiber in the manufacture of medium if we can retain more strength during fluting. Developments in this area will be discussed in a subsequent article.

## INTRODUCTION

Corrugating performance is limited by a number of factors, several of which directly affect board quality. For example, high-lows, flute fracture, bond quality and board strength all affect corrugator productivity, convertability and end-use performance of corrugated board. Hence, they are of great economic importance to the industry.

Trends to higher corrugating speeds are placing increasing demands on the forming characteristics of medium and our ability to bond the liners and medium. Concurrently our industry is directing attention to improving the end-use performance characteristics of linerboard and medium through changes in papermaking. In these developments it is necessary to make sure that high speed runnability on the corrugator is maintained or improved. To achieve this goal, it is necessary to have a good understanding of the relationships between containerboard properties, forming, and bonding.

During fluting the medium is exposed to high stresses. If these stresses are too high, visible fractures of the medium will occur and the board will be useless. At lower stress levels visible fracturing will cease, but our research shows that there is still heavy damage to the medium, resulting in a serious loss of end-use performance.

This was discovered during our work on the cold corrugating process (1,2). We found that most of the properties of the cold-formed board were comparable to those of hot-formed board, but some mediums exhibited lower ultimate flat crush strengths when formed cold. In seeking the cause of this difference, we found that both hot and cold fluting caused large losses in the edgewise compressive strength of medium. As a consequence, some 30-40% of the flat crush potential of the medium and 15-20% of the ECT potential are lost during fluting. The effects of the fluting stresses on these losses are the subject of this article. Attention will be centered on the hot corrugating process. A second article will identify those medium properties which affect losses during fluting and papermaking changes to improve these properties so that more of the inherent potential of the medium can be retained through the fluting process.

## BACKGROUND

In its simplest concept, fluting is a forming operation. The medium is drawn under tension into the nip between the corrugating rolls, termed the labyrinth. In the labyrinth, the medium is shaped to the flute contour under the prevailing stress, temperature, and moisture conditions. At the center of the labyrinth high transverse compressive forces are applied to the medium which serve to help set the fluted shape.

Direct tensile stresses are induced in the medium by the applied brake tension and the frictional drag on the medium as it is drawn over the flute tips. McKee and Gander (3,5) showed that friction causes the web tension near the center of the labyrinth to be much greater than the applied brake tension. This has been confirmed by others (4,6), as well. Some investigators have shown that increasing the brake tension causes fractures to occur at lower speeds and reduces board strengths (2-4,7,8).

Bending the medium around the flute tip contour induces tensile stresses on the convex side of the medium and compressive stresses on the concave side. For pure bending, conformity to the flute tip contour requires bending strains that are greater than the MD stretch of the medium (3,6). These strains would be expected to cause fiber-to-fiber bond damage to the medium with a subsequent reduction in end-use performance of the combined board. This is particularly true because the relatively lower strength of medium in compression (9) was not taken into account in the bending strain estimate above. The pure tensile strains induced by web tension combine with these bending strains to increase total strain on the tensile side and reduce total strain on the compressive side. Acting together, these strains would be sufficient to cause fracture failure in almost every case, but fortunately shear strains are also induced in the medium as it conforms to the flute contour. It is believed these help by reducing the net strain below the stretch limit to permit forming without fracture (5).

At the center of the labyrinth, transverse compressive stresses applied to the medium are sufficient to reduce the tip and root caliper by about 35% (1). This action is similar to dry calendering which reduces sheet strength by disrupting fiber bonds.

McKenzie and Yuritta (10) have shown that the



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tensile strength of medium is reduced when it is formed in the Concora fluter. Their results indicate that the losses are independent of roll temperature but increase slightly with decreasing medium roll moisture content. Similar losses in tensile strength have been noted in Institute work. However, the effects of forming on the compressive properties of medium have not received attention, despite the importance of compressive strength to end-use performance.

In summary, the medium is exposed to relatively high tensile, bending, shear and transverse compressive stresses during fluting. We believe the stresses are high enough to affect fiber-to-fiber bonding thereby lowering combined board compressive and flat crush strengths.

## DISCUSSION OF RESULTS

### *Strength Comparisons of Formed and Unformed Mediums*

To characterize and quantify the strength losses incurred during fluting, considerable experimental work was carried out using four commercial 26-lb mediums: three semichemical and one recycled fiber. To determine the degree of compressive strength loss during forming, short span tests were made on fluted but unbonded sections of cold and hot formed medium. The compressive tests were made on the STFI short span compression tester which employs a test span of 0.7 mm (11). The short test span permits localized strength determinations which are of great value in studying formed flutes.

The machine direction STFI compressive strength results, taken at various positions around both hot and cold formed flutes, are shown in Fig. 1 and 2 for each of the four mediums. In each figure the upper dashed line represents the compressive strength for the unformed medium. The results show that all of the formed mediums exhibit reduced compressive strengths at all positions around the flute, although the losses are most severe at the tips and roots. Both hot and cold formed mediums show similar patterns, although there are some significant differences which are noted below. Overall the reductions in MD compressive strength were about 40%. We believe these reductions in compressive strength reflect fiber bonding damage caused by the high stresses in the forming process.

In Fig. 2 the MD compressive strengths in the flank and tip/flank regions (positions 2-4 and 6-8) tend to be reduced more by cold forming, especially on the trailing flank. These two mediums also exhibited lower flat crush when formed cold. For the mediums in Fig. 1, where the cold and hot flat crush results were comparable, the compressive strengths of the hot and cold formed mediums were also about the same.

Based on past observation and experiment, we believe it is reasonable to expect the flat crush load-deformation characteristics to be related to the MD edgewise compressive properties of the formed medium. Thus the lower ultimate flat crush strength obtained with some mediums under cold forming conditions can be explained in terms of the greater compressive strength degradation in the flank/tip and flank regions of the flute. This is illustrated by Fig. 3, which shows that the STFI compressive strengths of the tip/flank region are related to flat crush for hot or cold formed mediums. In contrast, the STFI compressive strengths of the uncorrugated mediums are not related to flat crush results for either forming method. This supports the hypothesis that degradation of MD edgewise compressive strength during forming is a major factor in reduced flat crush performance.

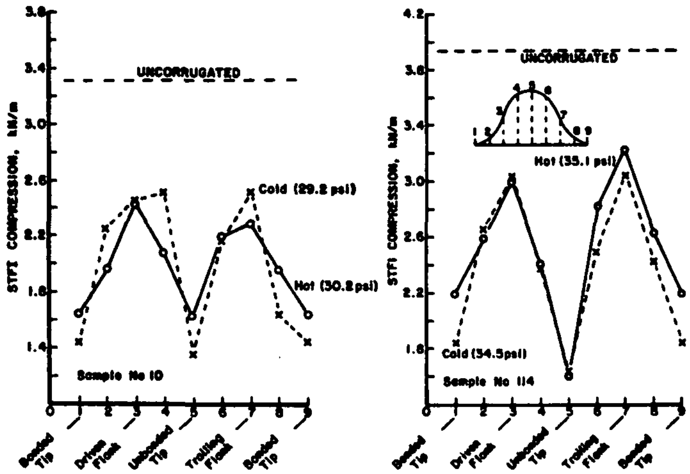


**Fig. 1** Machine direction compressive strength after fluting for mediums exhibiting "Equal" cold/hot flat crush ratios (flat crush values in parentheses).

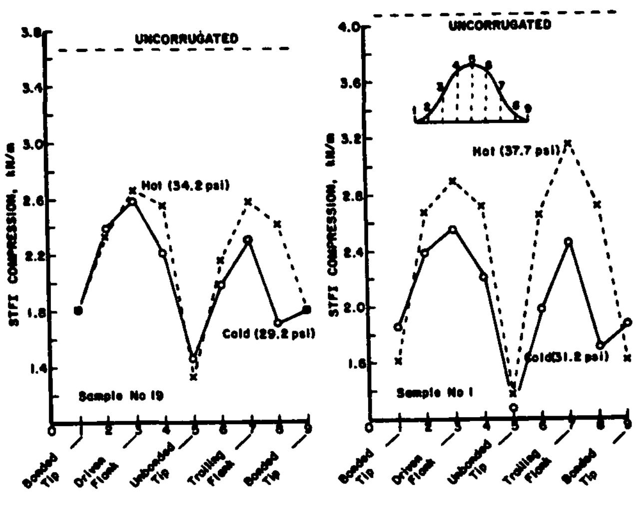


**Fig. 2** Machine direction compressive strength after fluting for mediums exhibiting "different" cold/hot flat crush strength (flat crush values in parentheses).

Short span MD tensile tests on the sample 1 hot formed medium also showed reductions in strength, ranging from about 17-44% as compared to the uncorrugated medium (Fig. 4). In all cases studied the percentage reductions in short span tensile strength were less than in edgewise



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compression. Thus, while forming affects both the short-span tensile and compressive characteristics of the medium, compressive strength is lowered more drastically, at least for speeds before the onset of fracturing. This may occur because compressive strength is sensitive to the shear stresses induced in the forming process.

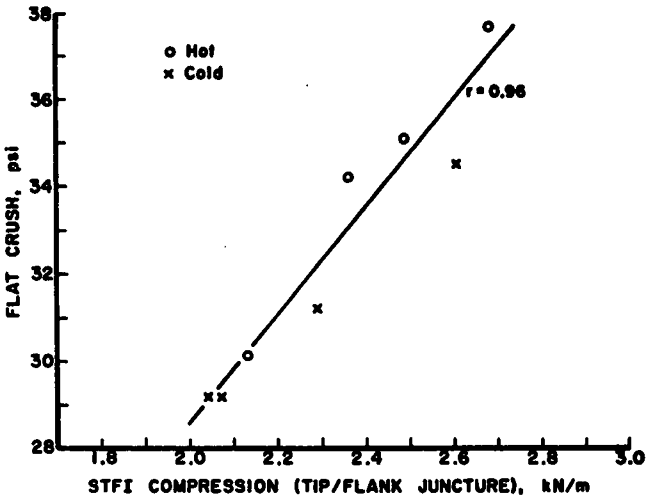


**Fig. 3** Relation between compressive strength of the fluted medium and flat crush.

Figure 4 also shows that the cold formed medium exhibits lower tensile strength than the hot formed medium in all flute positions. The tensile strengths, however, vary more erratically with flute position than do compressive strengths. In any case, the reductions in tensile strength do not appear to be directly related to the losses in flat crush potential, although they may affect other board qualities.

STFI edgewise compressive tests were also made in the cross-machine direction on both hot and cold formed mediums. Because the width of the sample clamp is about one flute length, separation by position on the flute was impossible. Figure 5 indicates that forming reduces the average CD compressive strength of the medium about 20%. These reductions are about equal for hot and cold corrugating. Since in many combined board grades, one-third or more of the top-to-bottom box compressive load is carried by the CD strength of the medium, it can be degraded by 7% or more by CD forming losses. These results are significant because they indicate that the corrugating process itself seriously degrades the MD and CD compressive strengths of the medium.

Internal bond strength values, measured by tests of the Viscosity-Velocity Product (VVP) type, were also significantly lowered by forming. It is likely that the reductions in edgewise compressive strength are related to these losses in bonding strength.

**Strength Losses from Simulated Forming Stresses**

As previously noted, several stress types are induced during forming. To determine the relative significance of each in causing strength losses, a number of special prestressing tests were carried out.

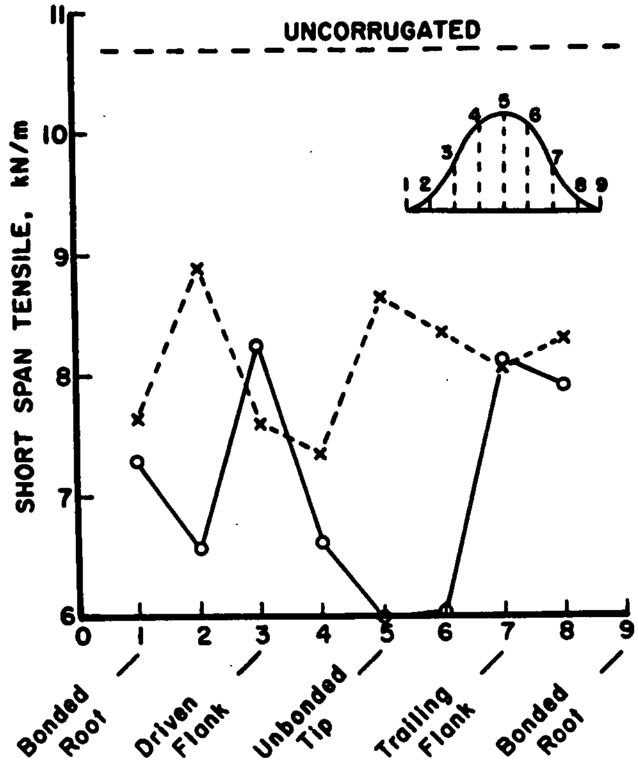


**Fig. 4** Effect of forming on short span tensile for sample 1. Compressive strength results for this sample are shown in Fig. 2. (Dashed line = hot formed; solid line = cold formed.)

We first loaded MD specimens of unformed medium in tension to failure. The remnants were then evaluated for compressive strength. Figure 6 shows that prestressing in tension produces no significant degradation in compressive strength, making it an unlikely candidate for causing compressive strength losses.

In corrugating, the onset of visible fracturing occurs gradually over a range of speeds. Fractures also usually occur locally and rarely propagate across the web as in tensile tests. Within the corrugating labyrinth, the medium may be stretched locally far enough to produce bond damage and hence affect compressive strength, but with insufficient stored energy to cause to propagate tensile fractures.

Flexing a medium around a small radius induces bending and shear stresses similar to those incurred in forming. We carried out such experiments. Figure 7 shows that such preflexing greatly reduces the MD compressive strength of the medium. The smaller the radius, the greater the loss in compressive strength. These results suggest bending is a likely contributor to the losses in MD compressive strength. Because the tip and root radii of the corrugating rolls are in the range of about 0.060 inch, both bending and shear stresses would be involved.

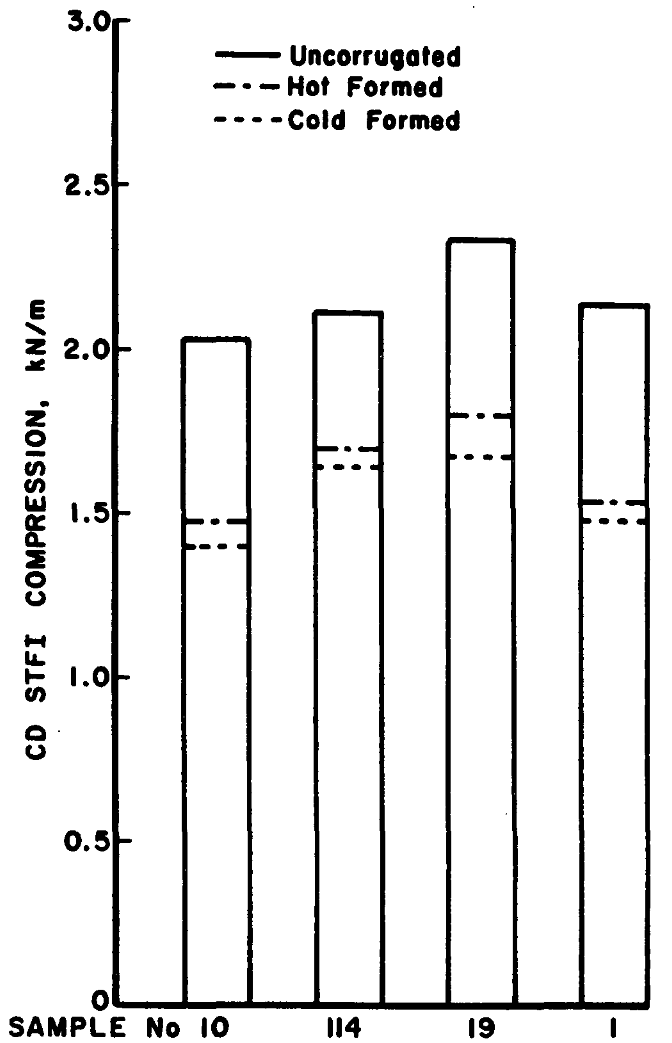


Fig. 5 Effect of forming on cross-direction edgewise compressive strength.

The combined effects of bending and tension stresses are illustrated in Fig. 8, which shows that the compressive strength decreases rapidly as the wrap angle increases from 0 to 90°. Wrap angles around the flute tip in a corrugator are about 90-120° near the center of the labyrinth (6,7). These angles are large enough to cause a significant loss in strength. The results in Fig. 8 also show that the losses in compressive strength are increased by higher tensions and smaller radii. Past work has shown that high web tensions occur in the corrugating labyrinth as a result of friction between the medium and steel rolls.

The moisture content of the medium at the time of forming will also affect stiffness and moldability. Higher moisture contents should permit the medium to be bent to the flute radius with less damage, assuming that friction is held constant or reduced.

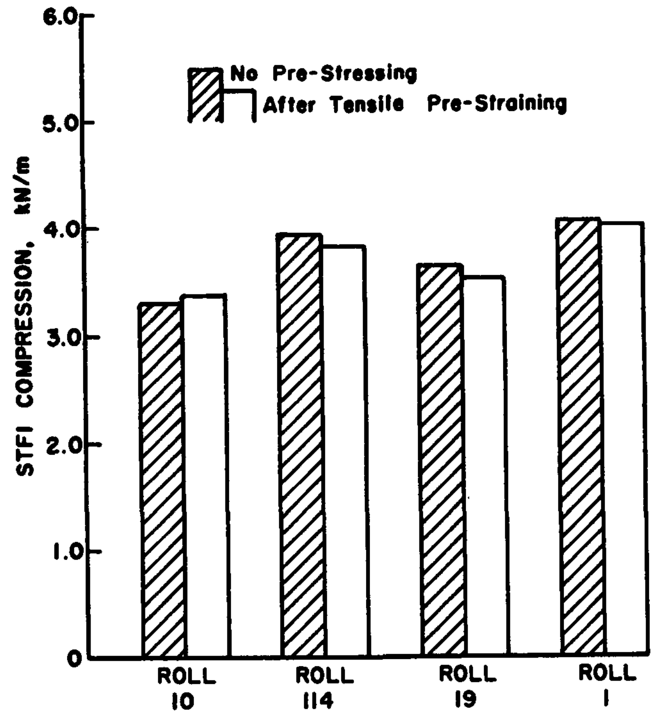


Fig. 6 Effect of tensile prestressing of MD edgewise compressive strength.

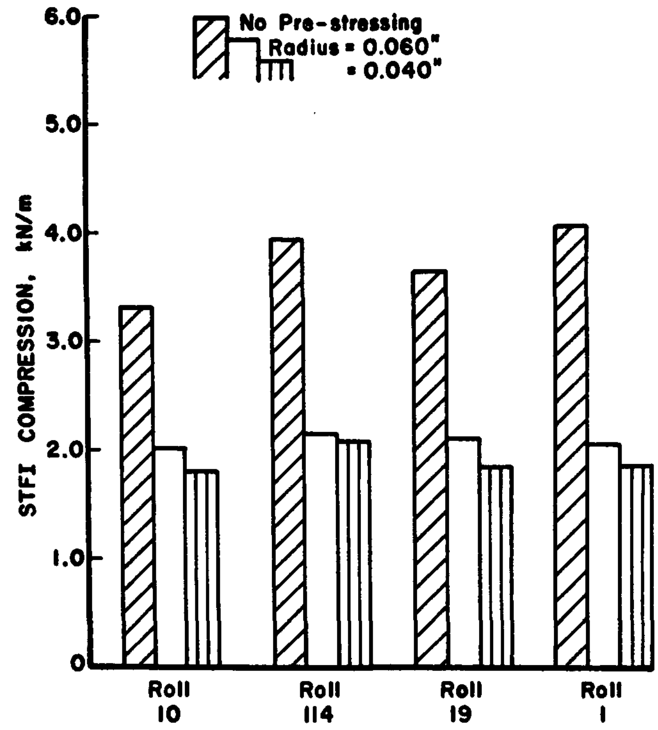


Fig. 7 Effect of bending prestressing on MD compressive strength.

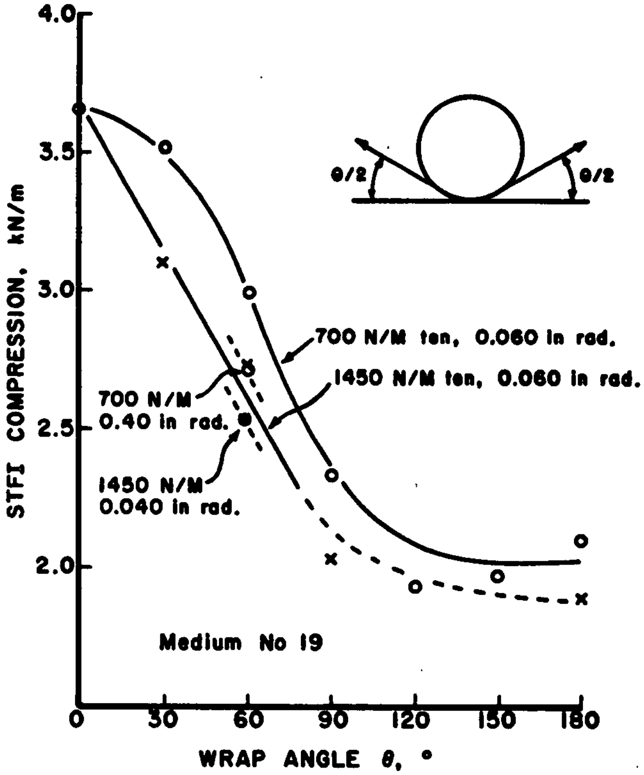


Fig. 8 Effect of tension and flexing conditions on MD compressive strength.

## EXPERIMENTAL

### Materials

Four commercial 26-lb/1000 $ft^2$ (ca. 127 $g/m^2$) mediums were selected for use:

1. Roll No. 1, semichemical
2. Roll No. 10, semichemical
3. Roll No. 19, semichemical
4. Roll No. 114, recycled fiber

Sample rolls 10 and 114 exhibited comparable flat crush levels under both hot and cold corrugating conditions. Sample rolls 19 and 1 exhibited lower flat crush under cold conditions than under hot conditions.

### Corrugating

Each roll was corrugated in The Institute of Paper Chemistry's experimental corrugator under both hot and cold conditions. In the "hot" runs the corrugating rolls and preconditioner were maintained at 350°F and the steam showers were used. In the cold runs the preconditioner and corrugating rolls were at room temperature. The mediums were treated on both sides prior to the fluting with a solid "slip" agent comprised of paraffin wax, graphite, stearin, and silicone.

Samples of the formed but unglued medium and single-faced board were obtained at a speed of 200 fpm under both hot and cold conditions.

### Test Procedure

The uncorrugated mediums were characterized in terms of a wide array of physical properties as given in Table 1. TAPPI test procedures were employed where available.

**Table 1 Properties of the uncorrugated medium**

| | | Roll 10 | Roll 114 | Roll 19 | Roll 1 |
|---|---|---|---|---|---|
| Basis weight, $g/m^2$ | | 126.9 | 137.7 | 128.4 | 127.4 |
| Caliper[b], m | | 259 | 274 | 272 | 234 |
| Density, $kg/m^3$ | | 486 | 496 | 467 | 538 |
| Concora crush, N | | 232 | 297 | 283 | 342 |
| Coeff. of friction[a] | 73°F | 0.58 | 0.52 | 0.54 | 0.54 |
| | 310°F | 0.44 | 0.24 | 0.25 | 0.28 |
| STFI compressive strength, kN/m | MD | 3.31 | 3.94 | 3.66 | 4.08 |
| | CD | 2.03 | 2.11 | 2.34 | 2.14 |
| Tensile strength, kN/m | MD | 4.52 | 9.38 | 6.11 | 7.56 |
| | CD | 2.29 | 3.06 | 2.98 | 2.61 |
| Stretch, % | MD | 0.94 | 1.42 | 1.22 | 1.04 |
| | CD | 1.30 | 4.24 | 1.79 | 2.57 |

[a]Kinetic coefficient between medium and a reference steel surface (IPC procedure).
[b]TAPPI T 411.

## CONCLUSIONS

(1) The edgewise compressive strength of fluted medium is reduced by the fluting operation in both the machine and cross-machine directions. The reductions range from 35-50% in the MD, while the CD compressive strengths are reduced about 20%. This degradation of compressive strength in both directions decreases box compressive strength, flat crush strength, and other combined board properties.

(2) Simulation experiments reveal that prestressing the medium in bending is probably the greatest factor in reducing edgewise compressive strength. The compressive strength losses are increased further by higher tensions during bending. Greater losses occur as the radius of bend decreases because the strain in the outer fiber layers is inversely related to the radius. These results suggest that the compressive strength losses in the medium - and hence ECT and flat crush losses in the combined board - are due primarily to bending stresses induced during forming.

(3) The transverse bonding strength of the medium



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is also reduced by forming. This is consistent with the hypothesis that fiber-fiber bond breakage occurs in the fluting operation.

(4) All mediums tested showed a strong correlation between flat crush strength and the remaining compressive strength in the flank/tip region of the flute after forming. Some mediums showed evidence of greater compressive strength reduction when formed cold. We believe this accounts for the lower flat crush obtained with these mediums under cold forming conditions.

## ACKNOWLEDGMENTS

This research was carried out at The Institute of Paper Chemistry (IPC) as part of basic studies on the fluting process and to support development of the cold corrugating process. The latter development was carried out under the sponsorship of the IPC, the Fourdrinier Kraft Board Group, and the Department of Energy, with the active support of the Union Camp Corporation.

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